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I HEREBY CERTIFY that annexed hereto is a true copy of documents filed in connection with the following patent application:

Application No.	S990793
Date of Filing	23 September 1999
Applicant	THE PROVOST, FELLOWS AND SCHOLARS OF THE COLLLEGE OF THE HOLY AND UNDIVIDED TRINITY OF QUEEN ELIZABETH NEAR DUBLIN an Irish Registered Charity of Dublin 2, Ireland.

PRIORITY DOCUMENT

SUBMITTED OR TRANSMITTED IN COMPLIANCE WITH RULE 17.1(a) OR (b)

Dated this 9 day of October, 2000.

Richard O'Halloran

An officer authorised by the
Controller of Patents, Designs and Trademarks.

FORM NO. 1

REQUEST FOR THE GRANT OF A PATENT

PATENTS ACT, 1992

S990793

The Applicant(s) named herein hereby request(s)

[ ] the grant of a patent under Part II of the Act

[x] the grant of a short-term patent under Part III of the Act

on the basis of the information furnished hereunder.

1. Applicant(s)

Name: THE PROVOST, FELLOWS AND SCHOLARS OF THE COLLEGE OF THE HOLY AND UNDIVIDED TRINITY OF QUEEN ELIZABETH NEAR DUBLIN

Address: Dublin 2,
Ireland.

Description/Nationality: An Irish Registered Charity.

2. Title of Invention: "Optical waveguide and a method for manufacturing a waveguide"

3. Declaration of Priority on basis of previously filed application(s) for same invention (Sections 25 & 26)

Previous filing date	Country in or for which filed	Filing No.

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4. Identification of Inventor(s)

Name(s) of person(s) believed by Applicant(s) to be the inventor(s)

JAMES CHRISTOPHER O'GORMAN, PAUL MCEVOY, DAVID MCDONALD, FREDERICK PAUL LOGUE and PASCAL MICHEL LANDAIS

Address

9 Portersgate Rise, Clonsilla, Dublin 15, Ireland;
8 Tennyson Court, Royston, Hertfordshire SG8 5SZ, England;
17 Drummartin Park, Dundrum, Dublin 14, Ireland;
Whitecross, Julianstown, County Meath, Ireland; respectively, all Irish citizens, and
3 Hatch Place, Dublin 2, Ireland, a French citizen.

CONTINUED OVER

5. Statement of right to be granted a patent (Section 17 (2) (b))

The applicant has derived the right to be granted a Patent from the inventors by virtue of Deeds of Assignment dated September 22, 1999.

6. Items accompanying this Request - tick as appropriate

(i) [x] Prescribed filing fee (£ 50.00)

(ii) [ ] Specification containing a description and claims

[x] Specification containing a description only

[x] Drawings referred to in description or claims

(iii) [ ] An abstract

(iv) [ ] Copy of previous application(s) whose priority is claimed

(v) [ ] Translation of previous application whose priority is claimed

(vi) [ ] Authorisation of Agent (this may be given at 8 below if this Request is signed by the Applicant(s))

7. Divisional Application(s)

The following information is applicable to the present application which is made under Section 24 -

Earlier Application No: ....
Filing Date: ....

8. Agent

The following is authorised to act as agent in all proceedings connected with the obtaining of a patent to which this request relates and in relation to any patent granted -

Name	Address
F.F. GORMAN & CO.	54 Merrion Square, Dublin 2, Ireland.

9. Address for Service (if different from that at 8)

F.F. GORMAN & CO., at its address as recorded for the time being in the Register of Patents Agents.

F.F. GORMAN & CO., Authorised Patent Agents

BY:______________________ EXECUTIVE

Signed Name(s) :
Capacity (if applicant is a body corporate) :

23 SEP 1999

Date September 23, 1999

APPLICATION No. S 990793

"Optical waveguide and a method for manufacturing a waveguide"

The present invention relates to an optical waveguide, and to a method for manufacturing the waveguide.

Such waveguides may be in the form of an optical filter, for example, for filtering laser light to provide laser light of a substantially single predetermined wavelength. Waveguides may also be in the form of semiconductor laser light generating devices. Where waveguides are provided in the form of a filter, such filters comprise an optical fibre core which defines an optical path of the filter. The optical fibre core is surrounded by a medium of refractive index different to that of the optical fibre core for retaining the laser light within the optical fibre core. Semiconductor laser light generating devices also comprise a waveguide which is formed by the optical path defined by the semiconductor laser device in which the laser light is generated. The waveguide in such a semiconductor laser light generating device in general is adapted to provide laser light output of a substantially single predetermined wavelength.

Optical waveguides incorporating wavelength selective characteristics are particularly useful components in optical technology. For example, optical fibre devices are useful for many applications in modern optical communications and sensing, in wavelength division multiplexing (WDM) and in other fibre optic applications. Fibre Bragg grating (FBG) devices, fibre lasers, Distributed Bragg reflector (DBR) devices and Distributed feedback (DFB) devices all have been used

previously as wavelength selective devices and sources for these applications. Wavelength selection is a key attribute in optical filters and light emitters. For example, Fibre Bragg gratings for wavelength selection and distributed feedback gratings for single wavelength or single mode operation of semiconductor lasers are key elements of WDM communications technology. In the optical fibre waveguide arena significant efforts have been made to devise new grating structures for new component functionality or improved performance of existing components. In the semiconductor laser arena, Fabry Perot (FP) cavity lasers have many advantages over other laser types in terms of cost and ease of processing but have poor single mode performance. Consequently, efforts have been made to devise a FP laser which has sufficient single mode character to be used in the abovementioned applications.

Laser diodes with single wavelength emission properties are also known. One approach to obtaining single longitudinal mode FP lasers is described by Coldren *et al.* (L. A. Coldren, B. I. Miller, K. Iga and J. A. Rentschler in *Applied Physics Letters* (1981), **38**(5), 315 - 317; K. J. Ebeling, L. A. Coldren, B. I. Miller and J. A. Rentschler in *Applied Physics Letters* (1983), **42**(1), 6 - 8) divided a GaInAsP laser into two coupled sections by forming a shallow groove in the semiconductor material by reactive ion etching. For a configuration where two sections (of lengths l_1 and l_2) are separated by a groove of about 1μm width and l_2/l_1 = 1/8, it is found that every eighth mode in the emission spectrum is enhanced while the intervening modes are suppressed. This discrimination between modes, leads to essentially single mode operation. The possibility of "multi-element" or multi-cavity section lasers is disclosed.

DeChiaro (L. F. DeChiaro: *Journal of Lightwave Technology* (1990), **8**(11), 1659 - 1669; and *Journal of Lightwave Technology*(1991), **9**(8), 975 - 986) discloses that operation approaching single longitudinal mode operation, with side mode suppression of 20 dB can be obtained by the introduction of absorbing regions at appropriate locations along the active layer of a ridge waveguide device. The absorbing defects are created in the active layer using a pulsed xenon laser focused on the active stripe of the waveguide. It is suggested that reduced spectral width operation approaching single-mode operation can be achieved by placing N absorbing sites along the active region with the n^{th} site located at the distance $L/2^n$ from one of the laser facets (where L is the length of the cavity).

Kozlowski and Young *et al.* (D. A. Kozlowski; J. S. Young; J. M. C. England and R. G. S. Plumb: *Electronics Letters* (1995), **31**(8), 648 - 650 and *IEE Proceedings: Part J. Optoelectronics* (1996), **143**(1), 71 - 76; J. S. Young; D. A. Kozlowski; J. M. C. England and R. G. S. Plumb: *Electronics Letters* (1995), **31**(4), 290 - 291) have disclosed that pits etched by a focused Ga^+ ion beam along the lasing region of a FP device to simulate reflective and nonradiative defects result in quasi-single mode operation with 30 dB side mode suppression with a negligible rise in the threshold current. With defect sites introduced at fractional positions (1/2, 1/4 and 1/8 the cavity length) scattering caused by the defects modifies the gain profile enhancing some modes and suppressing others. It is acknowledged that the position and depth of the pits, dependent on the reliability of the focussed ion beam etching process used to form the pits, are crucial to the operation of the device.

Corbett and McDonald (B. Corbett and D. McDonald: *Electronics Letters* (1995), **31**(25), 2181 - 2182; D. McDonald and B. Corbett: *IEEE Photonics Technology Letters* (1996), **8**(9), 1127 - 1129) disclose a technique for converting the multi-longitudinal mode output of 1.3 µm ridge waveguide FP laser into a single mode by introducing refractive index perturbations along the length of the ridge. These perturbations are in the form of slots etched into the guide ridge, with a controlled depth and location relative to the total physical length of the device, forming a number of sub-sections in the laser cavity. The slots do not reach the active region of the laser, but cause refractive index perturbations at defined positions along the length of the cavity causing some optical modes to undergo reflection. Optical frequencies that are resonant with any of the sub-section lengths are enhanced. A multi-mode laser having slots located at positions of 1/2, 1/4 and 1/8 of the total physical cavity length is found to exhibit quasi single mode behaviour with a side mode suppression ratio (SMSR) of up to 25 dB. The modes that satisfy the lasing condition for the modified cavity are reinforced and so have a lower threshold gain and reach threshold first.

However, all the above devices suffer from a disadvantage in that in general, they tend to be inefficient and do not adequately provide laser light output of a substantially single predetermined wavelength.

There is therefore a need for an optical waveguide and a method for manufacturing the optical waveguide which provides an optical waveguide which outputs laser light of a substantially single predetermined wavelength.

The present invention is directed towards providing such a waveguide and a method for manufacturing the waveguide.

According to the invention there is provided an optical waveguide for outputting laser light of a substantially single predetermined wavelength, the optical waveguide comprising a light conducting medium defining a longitudinally extending optical path for guiding the laser light, and a means for causing partial longitudinal reflections of the light at at least two spaced-apart locations along the optical path for deriving laser light of the predetermined wavelength, wherein the means for causing the partial reflections is located such that the spacing of the locations along the optical path at which the partial reflections occur is a function of the effective length of the optical path taking account of alteration in the actual length of the optical path resulting from the affect of the means for causing the partial reflections on the length of the optical path.

In one embodiment of the invention the means for causing the partial reflections causes the partial reflections at at least three locations along the optical path.

In one embodiment of the invention the means for causing partial longitudinal reflections of the light comprises a refractive index altering means for altering the effective refractive index of the light conducting medium presented to light at the at least two locations for causing the partial reflections.

Preferably, the respective locations at which the effective refractive index presented to the light in the optical path is altered are relatively localised locations.

Advantageously, the length of the locations at which the effective refractive index presented to the light in the optical path is altered are relatively short in the longitudinal direction of the optical path.

In another embodiment of the invention the refractive index altering means comprises a plurality of elements located at spaced-apart intervals along the optical path, but spaced-apart therefrom. Advantageously, the spacing of the elements along the optical path is a function of the effective length of the optical path taking account of the alteration in the effective refractive index presented to the light in the optical path.

In one embodiment of the invention each element is provided by a slot, and preferably, by a slot extending transversely relative to the direction of the optical path.

In one embodiment of the invention each slot is formed in a second medium adjacent the light conducting medium in which the optical path is defined.

In one embodiment of the invention the optical waveguide is formed in a ~~semiconductor laser generating device, and is formed by the optical path generated~~ by the semiconductor laser device.

In a further embodiment of the invention a ridge is formed on the surface of the laser diode above the optical path, and the transverse slots are formed in the ridge extending transversely of the longitudinal direction of the optical path. In one

embodiment the slots may be of the same or different widths. Advantageously, the slots may be of the same or different depths.

In one embodiment of the invention a plurality of optical waveguides are provided in the form of an array, and the number of locations along the respective optical paths at which the effective refractive indices presented to the light is altered may be the same or different.

In a further embodiment of the invention the waveguide is formed in a filter, the optical path being defined by an optical fibre core which forms the light conducting medium, and the optical fibre core is surrounded by the second medium, which is of refractive index different to the first medium, the elements being located in the second medium, and preferably, the elements are formed by slots located in an outer surface of the second medium, which preferably, extend transversely of the optical path, and advantageously around the second medium.

In a further embodiment of the invention the location of the pth location at which the effective refractive index presented to the light in the optical path is altered along the optical path is determined according to the following equation.

$$L_{left} = \frac{X\left(L_{device} n_{device} - \sum_{i} L_i \Delta n_i\right) + \sum_{i=1}^{p-1} L_i \Delta n_i + \frac{1}{2} L_p \Delta n_p}{n_{device}}$$

where: L_{left} is the physical distance from the pth element to the first boundary,

X is the fraction of the actual optical length at which the element is to be placed,

L_{device} is the physical length of the optical path,

n_{device} is the effective refractive index of the optical path presented to the light (unaltered),

L_i is the width of the i^{th} element,

Δn_i is the difference between the effective refractive index and the altered effective refractive index of the i^{th} element,

L_p is the width of the p^{th} element,

and Δn_p is the difference between the effective refractive index and the altered refractive index of the p^{th} element.

Additionally, the invention provides a method for manufacturing an optical waveguide for outputting laser light of a substantially single predetermined wavelength, the method comprising providing a light conducting medium defining a longitudinally extending optical path for guiding the laser light and presenting an effective refractive index to the light, providing a refractive index altering means for altering the effective refractive index of the first medium presented to the light at at least two spaced-apart locations along the optical path for causing longitudinal reflections of the light in the optical path for deriving laser light of the predetermined wavelengths, wherein the refractive index altering means is located such that the location of the p^{th} location at which the effective refractive index presented to the light in the optical path is altered along the optical path is determined according to the following formula:

$$L_{left} = \frac{X\left(L_{device}n_{device} - \sum_{i} L_i \Delta n_i\right) + \sum_{i=1}^{p-1} L_i \Delta n_i + \frac{1}{2} L_p \Delta n_p}{n_{device}}$$

where: L_{left} is the physical distance from the pth element to the first boundary,

X is the fraction of the actual optical length at which the element is to be placed,

L_{device} is the physical length of the optical path,

n_{device} is the effective refractive index of the optical path presented to the light (unaltered),

L_i is the width of the ith element,

Δn_i is the difference between the effective refractive index and the altered effective refractive index of the ith element,

L_p is the width of the pth element, and

Δn_p is the difference between the effective refractive index and the altered refractive index of the pth element.

The invention will be more clearly understood from the following description of an embodiment thereof which is given by way of example only with reference to the accompanying drawings:

Figure 1 shows a typical prior art ridge waveguide laser, having a slot in the waveguiding ridge,

~~Figure 2 is a side profile of the prior art laser depicted in Figure 1,~~

Figure 3 is a schematic diagram of a laser according to the present invention,

Figure 4 is a plot of threshold gain versus wavelength curves calculated for a

slot laser configuration with and without the optical correction technique of the present invention,

Figure 5 is a plot of facet output power versus operating current calculated for the 9 slot configuration referred to in the previous figure,

Figure 6 is a plot of side mode suppression ration versus operating current for the 9 slot configuration referred to in Figure 4,

Figure 7 is a plot of threshold gain versus wavelength curves calculated for a 3, 6 and 9 slot laser configurations according to the present invention,

Figure 8 is a plot facet output power versus operating current calculated for the 6 slot configuration referred to in Figure 7,

Figure 9 is a plot of side mode suppression ratio versus operating current for the 6 slot configuration referred to in Figure 7,

Figure 10 is a diagram of two slotted lasers differing only in the number of sots on the ridge,

Figure 11 is a laser array made up of a plurality of ridge waveguide lasers on a single semiconductor chip,

Figure 12 is a plot of threshold gain versus wavelength plots for an array of four lasers having 15, 17, 19 and 20 slots,

Figure 13 is a plot of threshold gain versus wavelength plots for a second array of lasers having 13, 15 and 19 slots, and

Figure 14 (a) to (c) are three plots of the power emitted from a device according to the invention, at different currents, as a function of wavelength.

In the description with reference to the drawings similar components are identified by the same reference numerals. Additionally, in the embodiments of the invention described below the refractive index altering means for altering the effective refractive index of the medium of the optical path presented to the light in the optical path is provided by a plurality of slots extending transversely of the optical path. It will of course be appreciated that any other refractive index altering means besides slots may be provided. Additionally it will be appreciated that other means for causing partial reflections along the optical path besides refractive index altering means may be used.

~~The term "slot" is to be taken to mean any refractive index altering means provided~~ on the surface or elsewhere of a semiconductor laser device or waveguide device.

The term "configuration of slots" is be taken to mean an arrangement of two or more slots the dimensions of each slot being the same or different.

The terms "perturbation of effective refractive index" or "perturbed region" when used in connection with a "slot", or other means for altering the effective refractive index of the medium presented to the light in the optical path relate to the region within the waveguide in which the effective refractive index has been altered due to the presence of the "slot" or other refractive index altering means.

The terms "cavity sections", and "unperturbed regions" are used to distinguish the sections within the optical path wherein the effective refractive index has not been altered.

Additionally, in the description of the embodiments of the invention with reference to the drawings the terms "perturbed" and "perturbation" are used to refer to the alteration of the effective refractive index.

A multi-section semiconductor device according to the present invention, as described below, comprises a ridge waveguide having either a Fabry Perot structure with slots or grooves etched into its surface, a series of coupled cavity lasers, or a multi-contact device for example. Any device where the effective refractive index varies along the cavity may be considered as a multi-section semiconductor device for the purpose of the present invention. The introduction of one or more slots into the device may alter or perturb the refractive index of the laser cavity, causing a perturbation of the optical modes resonant in the cavity. The slot does not necessarily have to penetrate into the guiding core, namely, the optical path for it to have this affect. In the general case, perturbation of the effective refractive index of the cavity need not be caused by the introduction of slots, but may suitably be

caused by any alternative means. For example, the perturbation may be caused by an alteration of the physical structure of the laser by the introduction of ridges or doping, or by varying the pumping current at positions along the cavity. The means of perturbing the effective refractive index may be employed independently or in conjunction with one or more of said means. To avoid unnecessary repetition, this description can be easily applied by those skilled in the art to other waveguide devices such as fibre waveguides or passive semiconductor waveguides. The following description of the present invention refers without loss of generality to the specific case where the perturbation of the effective refractive index is caused by the introduction of slots into a semiconductor laser light generating device.

Figure 1 shows a typical prior art semiconductor laser 1 made up of a layer structure comprising an active region 2, namely, an optical path sandwiched between a substrate 3 and a top layer 4. Those skilled in the art will be familiar with such structures and will be aware that the active region and other layers are in general more complex than shown in the figure, being made up of different arrangements of sub-layers. The layer structure has first and second mirror facets 5 and 6 produced when the chip used to form the laser device is cleaved from the semiconductor wafer. The mirror facets may or may not be coated. Electrical contacts (not shown) are attached to the top layer 4 and the substrate 3 to facilitate electrical pumping of the active region 2.

In the ridge waveguide laser structure shown, a ridge 7 is defined on the top surface 8 of the top layer 4. This may typically be achieved by etching two channels 9 along the length of the device thereby defining a ridge 7 between said channels 9. The

affect of the ridge 7 is to guide the laser emission within the device and to guide the output below the ridge to a small area 10 of the facets 5 and 6. The presence of the ridge 7 leads to single transverse mode emission from the device 1. The ridge 7 has been modified by the introduction of a slot 12 which is positioned substantially perpendicularly to the direction of said ridge 7. The position and size of the slot are defined by the distances L_{21} and L_{22} from the facets 6 and 5 respectively and the slot width, L_i. In prior art devices the dimensions L_{21} and L_{22} are defined in terms of the overall physical length of the device. The laser emission is depicted by the cone and arrow 11.

Figure 2 shows a side profile of a prior art laser similar to that shown in Figure 1. In the interest of clarity the proportions of individual components (such as the thickness of the different layers etc.) have been changed. The depth of the slot 12 may vary, with the slot 12 reaching or extending into the guiding or active region 2 if desired. The affect of the slot 12 (or slots, where more than one slot is introduced into the structure) is to modify or perturb the effective refractive index of the waveguide in the vicinity of the slot, indicated by the shaded region 13.

The procedures for manufacturing semiconductor devices are well documented in the literature and will be familiar to those skilled in the art.

The optical field of radiation propagating along the laser waveguide propagates differently through the sections of the laser depending on the effective refractive index of each section. As mentioned above, the introduction of a slot 12 into the structure causes a perturbation of the effective refractive index in the vicinity of said

slot. The effective refractive index of the perturbed region 13 will be different to that of the unperturbed cavity sections. In the case where the perturbation of the effective refractive index is caused by a slot, the effective refractive index experienced by the various laser modes in the perturbed region 13 will be different from that of the unperturbed regions. As a result, a partial reflection of selected modes will occur at the interface between said unperturbed and perturbed regions. These reflections can be used to tailor the mode spectrum in the device.

However, another affect of the slots, and the perturbations in the effective refractive index of the cavity associated with them, is that they change the effective optical length of the cavity. This change in the optical length of the cavity is particularly significant when more than one perturbation is positioned along the cavity if the physical length between the boundaries of the device or cavity is used to define the positions of the slots (and hence the perturbations). Due to the perturbation of the effective refractive index along the entire cavity, the physical positions at which the slots are to be placed no longer correspond to the optical positions, i. e. a configuration of slot positions defined as 1/2, 1/4 and 1/8 of the physical cavity length, say, is different from a configuration of 1/2, 1/4 and 1/8 based on the optical length of the same cavity. To position the perturbations at the optical positions the affect of all perturbations to be placed in the cavity on the optical path length must be taken into account.

When there are a number of perturbations along the cavity the optical length, L, of the cavity may be given as:

$$L = L_{device} n_{device} - \sum_i L_i \Delta n_i \qquad \text{Eq. 1.}$$

where : L_{device} is the physical length of the cavity;

n_{device} is the effective refractive index of the device (unperturbed);

L_i is the width of the i[th] slot;

Δn_i is the difference in effective refractive index between the unperturbed section and the i[th] slot.

By working from one end of the device, i. e. either of the device waveguide boundaries or mirror facets 5 or 6, and calculating the optical length to the position of each of the perturbations, a formula can be derived to define exactly where to place the perturbation or slot. At the p^{th} perturbation along the device the optical length to the left L_{left} (i.e. starting at mirror facet (6) for the device shown in Figure 3) is calculated using the equation:

$$\mathrm{L}_{left} = L_{left} n_{device} - \sum_{i=1}^{p-1} L_i \Delta n_i - \tfrac{1}{2} L_p \Delta n_p \qquad \text{Eq. 2.}$$

where: L_{left} is the physical distance from the p[th] slot to the first mirror facet or waveguide boundary and the other quantities are as defined above.

The actual position, in terms of the physical length of the device, at which the slot should be placed is then:

$$L_{left} = \frac{X\left(L_{device} n_{device} - \sum_i L_i \Delta n_i\right) + \sum_{i=1}^{p-1} L_i \Delta n_i + \tfrac{1}{2} L_p \Delta n_p}{n_{device}} \qquad \text{Eq. 3.}$$

where: X is the fraction of the optical path length at which the perturbation is to be placed.

A laser comprising a number of slots in which the placement of said slots is defined by the above process can produce a substantially single longitudinal mode emission. This method of defining the placement of slots in terms of the optical length of the cavity will be referred to as "optical correction" in the remainder of this specification.

Figure 3 is a schematic diagram of a laser cavity 20 with left and right mirror facets 21 and 22. Cavity sections 23 to 28 are defined by the mirror facets 21 and 22 and a series of perturbed regions or perturbations 29 to 33 associated with the slots (not shown). In the particular device shown, the perturbations 29 to 33 are of equal width (L_i) and are positioned at equal intervals along the length of the cavity. However, in practice the size of perturbations (defined by the width and depth of the associated slots) may be the same or different for each one and the separation between perturbed regions may vary. The vertical dashed lines represent the centres of each of the perturbation. For the sake of the following description, it shall be assumed that the position of each perturbation is measured from the centre of the perturbation. A number of modes of light are resonant within the cavity. As described above the propagation of these modes within the cavity is governed by the effective refractive index of the material in the device. Prior art devices are known which incorporate a number of slots. The positioning of these slots (and thus the perturbations) is crucial to the mode profile of the laser emission. Slot positions in prior art devices are based on the physical length of the device, whereas lasers of the present invention are based on the optical path length of the device. This has a

significant affect on the single longitudinal mode character, specifically the side mode suppression ratio, of the device which is greater (for a given structure) in devices according to the present invention.

Having regard for Figure 3, a particular mode propagating within the waveguide in the direction from the left mirror facet 21 to the right mirror facet 22 encounters the first slot 29 and a first reflected portion 34 of said mode is reflected due to the change in effective refractive index caused by said perturbation 29. A standing wave is set up between the left mirror facet 21 and the first perturbation 29. The remainder of the mode i. e. the transmitted portion (not shown) continues to propagate on towards the second perturbation 30 where a second reflected portion 35 is reflected. Due to optical correction incorporated into the structure of the device, the optical path length travelled by the second reflected portion 35 is exactly twice that travelled by the first reflected portion 34 and the standing wave set up by said second reflected portion 35 will be a harmonic of the standing wave formed by said first reflected portion 34. This process continues along the cavity for subsequent perturbations 31 to 33. The affect of this harmonic relationship between portions of the mode reflected by the changes in effective refractive index induced by the slots is to enhance this mode with respect to other possible lasing modes.

In the absence of optical correction, the optical path lengths travelled by the second and subsequent reflected portions is no longer an exact multiple of the path length of the first reflected portion. As a result, the mode is not enhanced to the same degree.

For a device with i perturbations of equal width L_i and refractive index change Δn, to emit a mode with a desired wavelength, λ, the following condition must be met:

$$\lambda = \frac{2}{m}\left[(L_{device} - iL_i)n_{device} + iL_i n_{slot}\right] \qquad \text{Eq. 4}$$

where m is an integer and all of the other parameters are as already defined.

For a cavity length L_{device}, and effective refractive index n_{device}, the larger the change in effective refractive index caused by a perturbation the more pronounced the affect of the perturbation will be.

The values of parameters L_{device}, n_{device}, i, L_i and Δn may then be chosen so as to yield a slot configuration where the desired wavelength corresponds to an emission mode. For semiconductor lasers L_{device} varies from 0.2 – 1mm although for fibre waveguide devices, the lengths may be up to several meters; n_{device}, depends on the nature of the material and may be from about 1.5 to about 5; Δn may be from 0.1 to 1, preferably from 0.4 to 0.8; i may be from 3 to about 60 and L_i may be from about 1 to about 20 μm, the lower limit being defined by the etching or other technique employed.

The final affect on the choice of i and L_i will be the spacing between the least suppressed modes. This spacing may vary depending on the slot structure, but for a structure of equally spaced perturbations it is given by the expression:

$$\Delta\lambda = \frac{i\lambda^2}{2\left(L_{device}n_{device} + pL_i\Delta n\right)} \qquad \text{Eq. 5}$$

where all the variables have been previously described.

For the more complicated structures, with slots of different widths and different effective refractive indices for each perturbation, the same method can be used but the second part of the optical length expression, $pL_i\Delta n$, needs to be replaced with the summation of changes in optical length $\sum_i L_i \Delta n_i$.

It is further envisaged that the optical correction technique described above may be utilised to manufacture passive ridge waveguides, fibre gratings and fibre lasers wherein perturbations or slots are positioned according to the technique already described depending on the desired operation wavelength. Similar to the lasers described above, the positions of the elements or slots along the waveguide are determined in relation to the effective optical length of the device. Particularly, the relationship expressed in Equation 3 above may be used to determine the positions of the slots along the ridge. Such a waveguide may be coupled to a separate conventional semiconductor laser or the laser and waveguide may be formed as a single unit using fabrication techniques known to those skilled in the art.

It is even further envisaged that the optical correction technique described above may be utilised to manufacture fibre optical waveguides and fibre lasers wherein perturbations or slots are positioned according to the technique already described depending on the desired operation wavelength. Similar to the lasers described above, the positions of the elements or slots along the waveguide or fibre are determined in relation to the effective optical length of the device. Again, the

relationship expressed in Equation 3 above may be used to determine the positions of the slots along the fibre. Such a fibre waveguide may be coupled to a separate conventional semiconductor laser or the laser and waveguide may be formed as a combined unit using fabrication techniques known to those skilled in the art. For such fibre waveguides the physical lengths of the device may be defined by the distance between the outermost slots of the sequence and the position of subsequent slots determined by reference to these.

As mentioned above, the position and number of slots in a device affects not only the single longitudinal mode behaviour of the device, but also the wavelength of the device output. The removal of a single slot 37(a) from the first device 30(a) in Figure 10 gives the structure illustrated by the second device 30(b). As a consequence of this difference in slot configuration the outputs (arrows 38 and 39) from the two devices 30(a) and 30(b), will differ in terms of their emission wavelengths.

Figure 10 shows two similar semiconductor laser devices 30(a) and 30(b) each comprising an active layer 31 sandwiched between a bottom layer 32 and a top layer 33. Cleaving the semiconductor wafer into chips defines first and second mirror facets 34 and 35. Each device 30 further comprises a ridge 36 located on the top of said top layers 33. In each case the ridge 36 is characterised by a plurality of slots 37 formed according to the present invention. In keeping with the present invention, the positions of the slots 37 along each ridge 36 are defined with respect to the optical path length of the device i.e. taking optical correction into account. The only difference between the two devices 30 shown is in the slot configuration. The first

device 30(a) has an additional slot 37(a), while the second device 30(b) has no slot in this position as indicated by the arrow 37(b).

Figure 10 shows two separate devices, however, two or more lasers may be formed on the same semiconductor chip to give an array of devices as shown schematically in Figure 11. Figure 11 shows a laser array 41 comprising an active layer 42 sandwiched between a substrate layer 43 and a top layer 44. Three ridges 47 to 49 are located on the top of the top layer 44. This array acts as three separate laser devices, the effective delineation of the three lasers is indicated by the dashed lines between each pair of ridges 47 to 49. As described above, the number and relative positions of slots affects the single longitudinal mode and emission wavelength characteristics of a laser. The three devices making up the array shown in Figure 11 each have a different number of slots 50 and thus yield three distinct wavelengths, indicated by arrows 54 to 56. For the sake of clarity, the figure shows the ridges formed on top of the top surface. However, in practice each ridge is generally formed by etching two parallel channels along the length of the device (as described above in relation to Figure 1). Waveguided channels can also be formed using etching of features to create a ridge or channel and regrowth of differing index material to give a buried waveguide or heterostructure. The method of the present invention of manufacturing a laser, facilitates the manufacture of a laser array comprising a plurality of lasers, each one with different emission characteristics, on a single chip. This represents significant advantages for application which require a number of different wavelengths. One such application is providing laser devices with wavelengths matched to ITU (International Telecommunications Union) grids.

The ITU guidelines for wavelength division multiplexing (WDM) optical transmission systems recommend the wavelengths and the channel spacing of WDM systems, catering for both repeatered and non-repeatered systems. The current system is based on a grid reference anchored at 193.1 THz, having additional channels spaced 100 GHz above and below this reference frequency. The current standard allows for a total of 41 channels at 100 GHz spacing. This spacing changes to 200 GHz for 4 channel systems or more, and to 400 GHz for 4 channel systems. A benefit of the current invention for this application is that for an array of lasers according to the present invention on a single chip having a nominally similar FP structure, which has been designed for 193.1 THz say, that by optimising the slot configuration of individual lasers within the array the lasing wavelength can be changed to another on the ITU grid which is 100, 200 or 400 GHz away from the grid reference. As a result, adjacent lasers on a laser array can have frequencies matching the ITU wavelength grid. This is very attractive from the point of view of implementing multi-wavelength sources.

An additional advantage of the method of manufacture according to the present invention is that it provides control of the emission characteristics of the device after the epitaxial layer growth phase of fabrication has been completed.

In Figure 11 the slot configurations on the ridges 57 to 59 are modified simply by sequentially removing slots from the end of the ridge nearest the second facet mirror 56. It is clear that the slot configuration may be modified by removing a slot from the centre of the structure, say, or by any other possible rearrangement of the slots

including changing the number, width and/or depth of the slots or by changing the distance between two or more of the slots

Typically, such a laser array consists of ridge waveguide lasers having 3μm wide ridges approximately 1.3 μm in height. The inter-ridge distance of lasers on the same bar is typically about 250 μm. Where the ridge is defined by etching two parallel channels (as shown in Figure 1 for instance) the channels are about 8 μm on either side of each ridge. The metallisation pattern is such that all lasers on the same array are electrically isolated and can be current driven independently. Otherwise, all other processing steps are standard as known to those skilled in the art.

The following examples provide further description of specific embodiments of the present invention.

Example 1

For a semiconductor ridge waveguide laser of total length 300 μm with 9 slots (each 1 μm in width) etched into the ridge at fractional positions of 1/16, 1/8, 3/16, 1/4, 5/16, 3/8, 1/2, 5/8 and 6/8. The positions of each slot in terms of actual distance from one mirror facet of the device to the centre of each slot, is given in Table 1 for (i) the case where no optical correction is taken into account (non-optically corrected); and (ii) the case according to the present invention where the slot positions are determined in relation to the optical path length of the device using the optical correction method according to the present invention (optically corrected).

The refractive index of the unperturbed sections of the device is 3.2031, with a step of 0.4 in refractive index between the perturbed and the unperturbed sections.

Fractional Position.	Distance from facet: non-optically corrected. (µm)	Distance from facet: optically corrected. (µm)
1/16	18.75	18.74
1/8	37.50	37.55
3/16	56.25	56.36
1/4	75.00	75.16
5/16	93.75	93.97
3/8	112.50	112.78
1/2	150.00	150.26
5/8	187.50	187.74
6/8	225.00	225.23

<u>Table 1</u>

~~Slot positions for non-optically corrected and optically corrected configurations.~~

Comparison of the data for the optically corrected and non-optically corrected cases shows that there are significant differences in the slot positions in the two cases. There is a systematic shift in the positions of all of the slots relative to each other and relative to the mirror facets. These shifts in the slot positions can affect the

output characteristics of the device in terms of both side-mode suppression ratio and emission wavelength. Changing the positions of the slots will also change the length of the section between any two slots.

The structures detailed in Table 1 were used to calculate the threshold gain curves shown in Figure 4. The solid line represents the structure according to the present invention where optical correction has been used and the dashed line represents a structure which is equivalent except that optical correction has not been used in determining the positions of the slots. The positions of the slots for these structures are shown in Table 1 above, columns 2 and 1 respectively. The threshold gain represents the gain required to overcome mirror losses in the device and lasing wavelengths having a lower threshold gain will reach the lasing threshold at lower pump levels and therefore will be emitted preferentially under these pump conditions. This is the basis of side mode suppression leading to substantially single longitudinal mode emission. In Figure 4 the degree or extent of suppression of side modes about a given mode is indicated by the difference in the threshold gain values for a mode of interest (say for example the mode indicated by the arrow, A) and the nearest modes on either side of this particular mode. It is clear from Figure 4 that the laser according to the present invention, based on optically corrected positioning of the perturbations in the effective refractive index of the cavity, exhibits superior side mode suppression than the prior structure in which the positions of the slots are based on the physical length of the device.

Figure 5 shows calculated light output, as represented by facet power, as a function of operating current calculated for the optically corrected 9 slot structure according to

the present invention detailed in Table 1. The 9 curves represent different possible longitudinal modes. It can be seen quite clearly that one mode in particular gives a considerably higher output than all of the others. This is representative of the single mode nature of the output. This is further illustrated by the side mode suppression ratio (SMSR) curve shown in Figure 6. This curve, again calculated for the optically corrected structure detailed in Table 1, shows the SMSR between the single mode which lases preferentially and the next nearest mode. At currents above about 20 mA the SMSR is calculated to be approximately 40 dB.

It should be noted from Figure 4 there is a significant difference (of the order of 3-4 nm) in the wavelength positions of the enhanced modes in the optically corrected and non-optically corrected structures. This is apparent despite the fact that the number of slots and the width and depth of the slots is the same in each case. The only difference between the two structures is the method used to position the slots along the length of the laser cavity. This feature is important when it is desired to produce a laser which emits at a specific wavelength.

<u>Example 2</u>

Figure 7 shows threshold gain curves calculated for lasers according to the present invention having three different slot configurations: the optically corrected 9 slot configuration detailed in Table 1 above, a 6 slot configuration and a three slot configuration. The slot positions for each configuration are given in Table 2. In each case the positions of the slots are based on the optical path length of the device taking into account perturbations in the effective refractive index caused by the introduction of the slots.

These configurations are based on a device having a length of 300 μm and the layer structure shown in Table 3 below. The ridge (etched into the top InP layer) is 3 μm in width and 1.1 μm in height. Slots are etched 1.3 μm into the top InP layer. For the 3 and 9 slot configurations the slot width is 1 μm. For the 6 slot configuration the slot width is 1.5 μm.

Fractional Position.	Distance from facet (μm).		Fractional Position.	Distance from facet (μm).
	9 slot structure	**3 slot structure**		**6 slot structure**
1/16	18.74	-	1/14	21.44
1/8	37.55	87.52	1/7	42.94
3/16	56.36	-	3/14	64.44
¼	75.16	75.10	2/7	85.95
5/16	93.97	-	3/7	128.82
3/8	112.78	-	5/7	214.44
½	150.26	150.13		
5/8	187.74	-		
6/8	225.23	-		

Table 2.

Slot positions for optically corrected configurations; threshold gain curves shown in Figure 7.

From Figure 7 it can be seen that the 9 slot structure gives the lowest threshold and largest gain difference between modes (i.e. side mode suppression) of the three structures. The 6 and 9 slot structures have been chosen to give an emission wavelength of approximately 1552.52 nm.

Figures 8 and 9 show the light output, as represented by facet power, as a function of operating current and the SMSR curve, respectively, calculated for the optically corrected 6 slot structure according to the present invention detailed in Table 2. As described in Example 1 for the 9 slot configuration, the curves represent different possible lasing modes. It can be seen quite clearly that one mode in particular gives a considerably higher output than all of the others. This indicates the substantially single mode nature of the output. In relation to Figure 9, currents above about 20 mA yield a SMSR of approximately 40 dB.

Layer	Composition	Thickness (μm)	Refractive index
InP	substrate (bottom)	-	3.1657
$Ga_{1-x}In_xAs_yP_{1-y}$	λ = 1.1 μm	0.075	3.2758
GaInAsP cladding	λ = 1.25 μm	0.03	3.3599
GaInAsP x4 Q.W.	x = 0.69; y = 0.82	0.008	3.4879
GaInAsP x3 bar.	λ = 1.25 μm	0.015	3.3599
GaInAsP cladding	λ = 1.25 μm	0.03	3.3599
GaInAsP	λ = 1.1 μm	0.075	3.2758
InP	-	1.3	3.1657
GaInAs	x = 0.53 (top contact)	0.1	-

Table 3.

Layer structure (bottom to top) of 3, 6 & 9 slot configured devices in Example 2. Q.W. = quantum well layers; bar. = barrier layers between quantum well layers; λ matched = consecutive layers are wavelength matched to the degree indicated.

Example 3

The emissions from a laser array as described above were simulated and the results are shown in Figure 12 as threshold gain versus emission wavelength. The array consists of four lasers comprising 15, 17, 19 and 20 slots respectively. The array was defined as follows: length = 400 μm; slot width = 1.34 μm; effective refractive index = 3.5; slot refractive index = 2.9. The emission wavelengths for each of the

lasers within the array structure are shown in Table 4. Figure 12 shows the threshold gain versus wavelength curves for the structures having 15, 17, 19 and 20 slots. By varying the slot configuration a laser having a desired wavelength may be produced. In addition to the plots shown in Figure 12, 16 and 18 slot configurations were examined and were found to give emissions at 1539.77 and 1538.19 nm respectively. According to the present invention therefore, an array of different laser structures on a single chip can yield a range of desired wavelengths by pumping individual lasers independently.

No. of slots	15	17	19	20
Emission λ (nm)	1540.56	1538.98	1537.40	1536.61

Table 4.

Emission wavelengths for various slot configurations, threshold gain curves shown in Figure 12

Example 4

Figure 13 shows a plot of the threshold gain versus wavelength curves calculated for ~~a second array of ridge waveguide lasers having from 13, 15 and 19 slots in the~~ waveguiding ridge. The array was defined as follows: length = 400 μm; slot width = 1.34 μm; effective refractive index = 3.5; slot refractive index = 2.9. The emission wavelengths are given below in Table 5.

No. of slots	13	15	19
Emission λ (nm)	1545.32	1543.73	1540.56

Table 5.

Emission wavelengths for various slot configurations, threshold gain curves shown in Figure 13.

As already described, slot configurations based on the physical length of the device (for example the prior art devices of Coldren *et al* and Corbett and McDonald) result in different slot placement compared to configurations based on the optical length of the device, according to the present invention. Furthermore, the action of a slot by reflecting selected modes in the device is to enhance certain modes of the output. By perturbing the effective refractive index of the whole device, the presence of slots alters the propagation of resonating radiation within the device. Resulting from this, if a device contains more than one slot and if the placement of said slots is based on the physical length, some of the slots will no longer be optimally placed to enhance particular modes as desired. This scenario is overcome by lasers based on the optical correction method according to the present invention.

A further consequence of omitting optical correction relates to the tolerance of the devices to processing errors. The modal output characteristics of a slotted laser device are dependent upon the slot width and depth as well as the number and position of the slots within the device and the lengths of the sections between each pair of slots. Small errors in these parameters during the fabrication of the device

can drastically alter the device output. There are two main processing errors associated with this type of laser, cleave errors and etching errors. Cleave errors result in errors in the overall length of the device and errors in the distances between either laser facet and the slot closest to the facet. Etching errors can result in errors in the slot width, position and depth. Changing the depth of the slot changes the effective refractive index of the slot, while changing the width of a particular slot alters the length of the active sections adjoining that slot and the overall optical length of the cavity. Changing the positions of the slot changes the mode profile due to changing the lengths of both the preceding and following sections.

If optical correction is not incorporated into the device most of the slots may not be positioned for optimal mode enhancement, as described above in relation to Figure 3. This affect may be further compounded by etching errors which may result in some of the slots being moved further from the optimum position. It is a feature of the present invention that optical corrections yields slot positions which are at the optimum positions (within manufacturing tolerances) unlike the prior art methods. Lasers according to the present invention, incorporating optical correction, are as a result more tolerant to etching errors.

Using optical correction in the positioning of the slots reduces the affect of an error in the positioning of individual slots. This results from the fact that optical lengths of sections are multiples of each other, and therefore in the optically corrected case an error in the position of one slot can be masked by the presence of many more slots. In addition, if a sufficient number of slots are incorporated into the device, the tolerance to cleave errors drops dramatically as the reiterated optical distances

within the structure cause a greater affect than the cleave to 1st slot distance. This is in direct contrast to the non-optically corrected case, which is highly sensitive to cleave errors.

Example 5

Seven slot lasers of length 550 µm were manufactured according to the following specification: slots etched at 1/14, 1/7, 3/14, 2/7, 3/7, 4/7 and 5/7 positions along the ridge (these fractional positions represent distances of 39.3, 78.6, 118.0, 157.3, 235.9, 314.5 and 393.1 µm along the ridge of the device. The method of fabricating such a laser is referenced in Corbett and McDonald and will be well known to those skilled in the art.

Figure 14 (a) to (c) shows the power output of one the lasers thus produced as a function of wavelength. The three different plots represent power output at three different operating currents. In each case it can be seen that the laser output is single mode, exhibiting good side mode suppression (typically in excess of 20dB).

The invention is not limited to the embodiments hereinbefore described which may be varied in construction and detail.

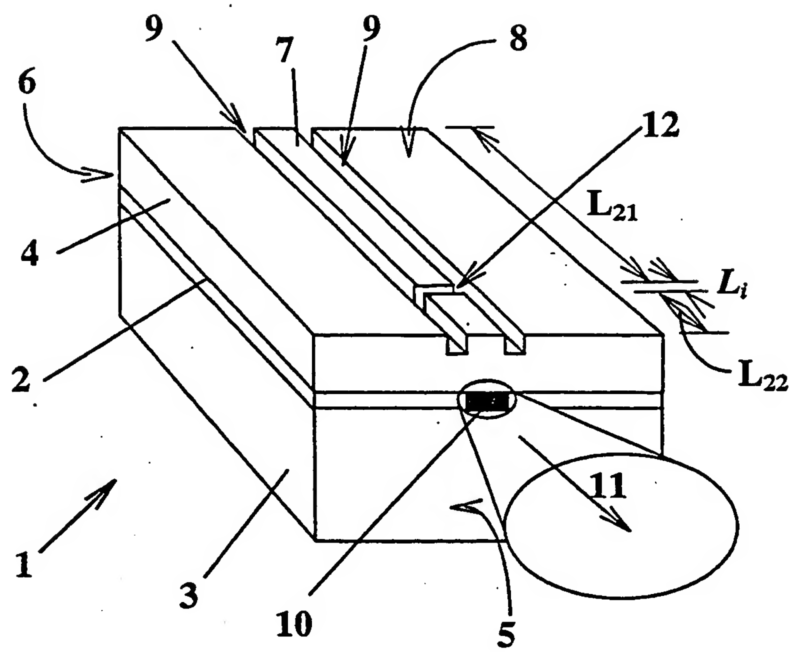


Figure 1. Prior Art.

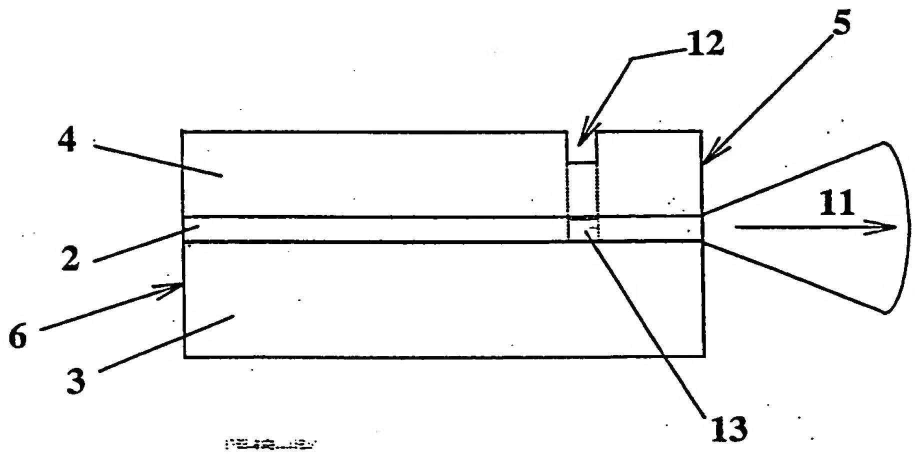


Figure 2. Prior Art.

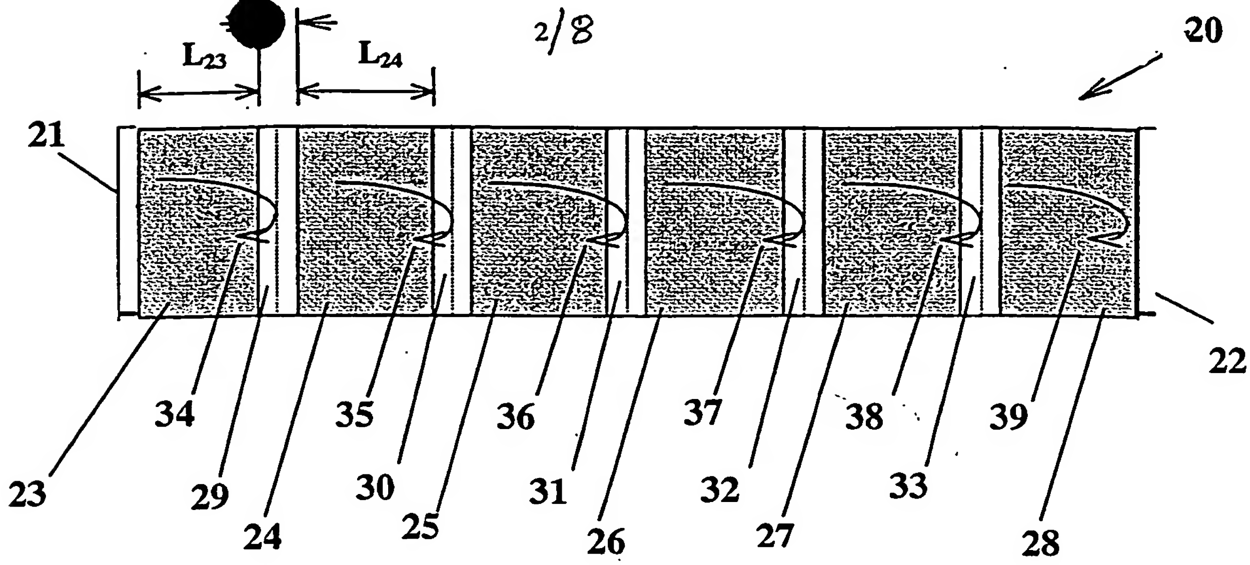


Figure 3.

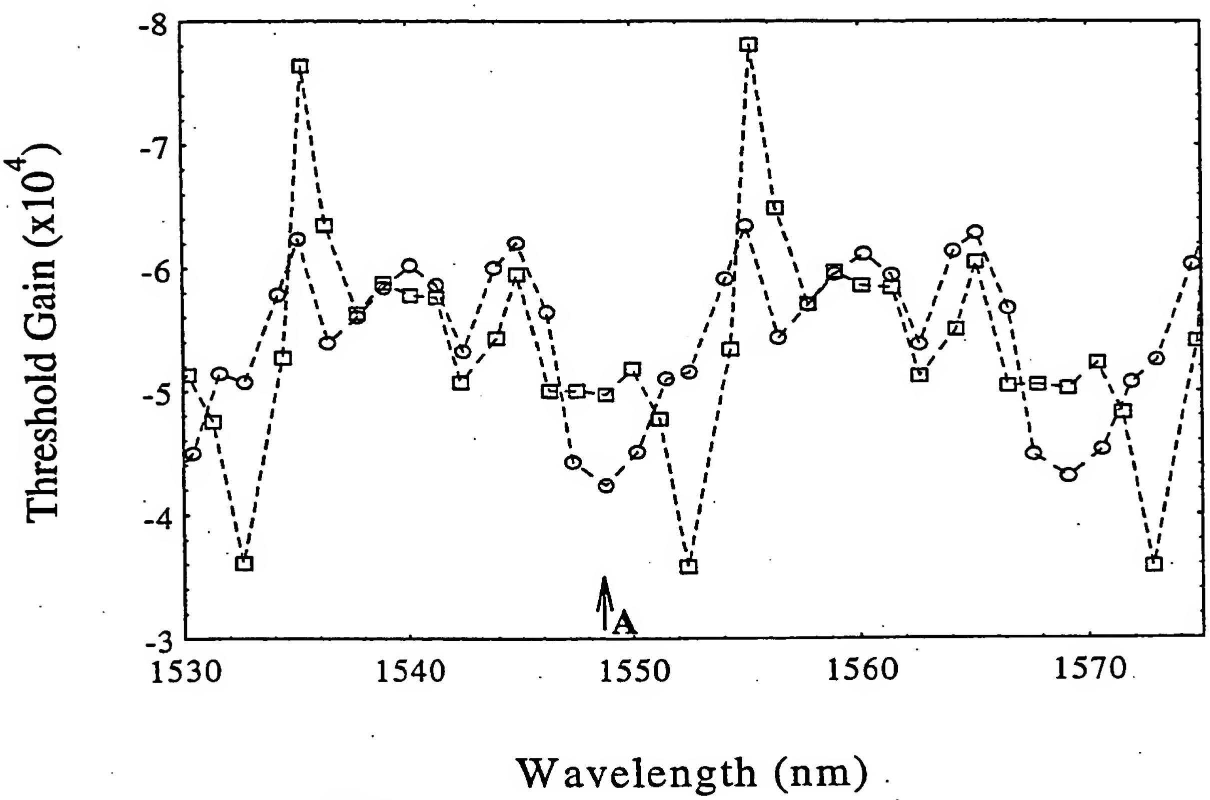


Figure 4.

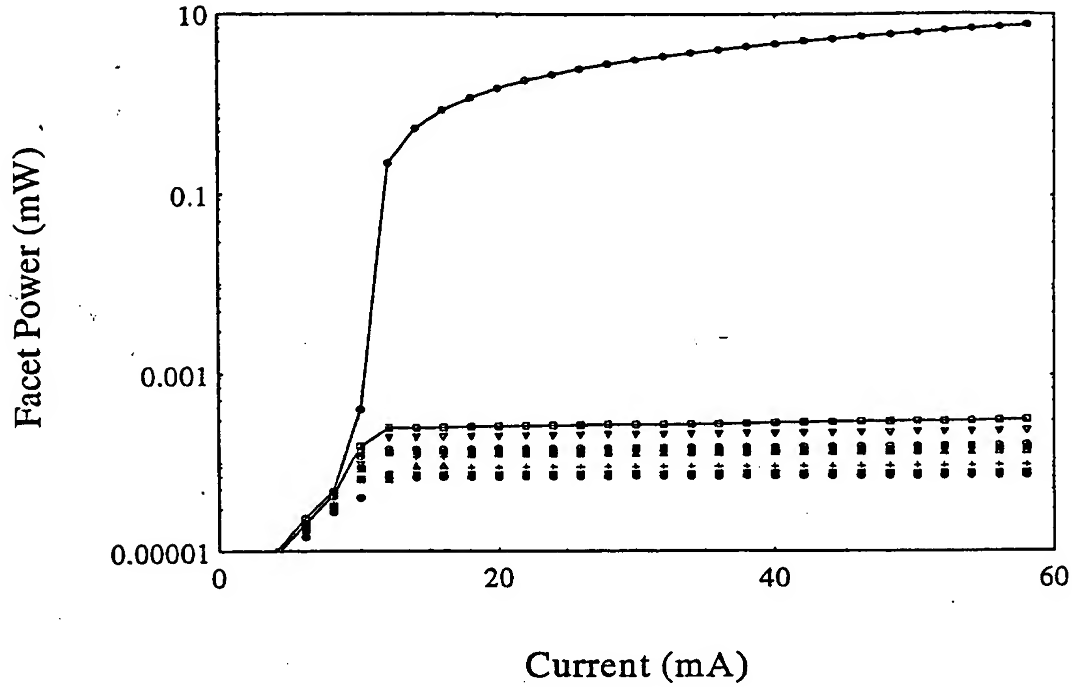


Figure 5.

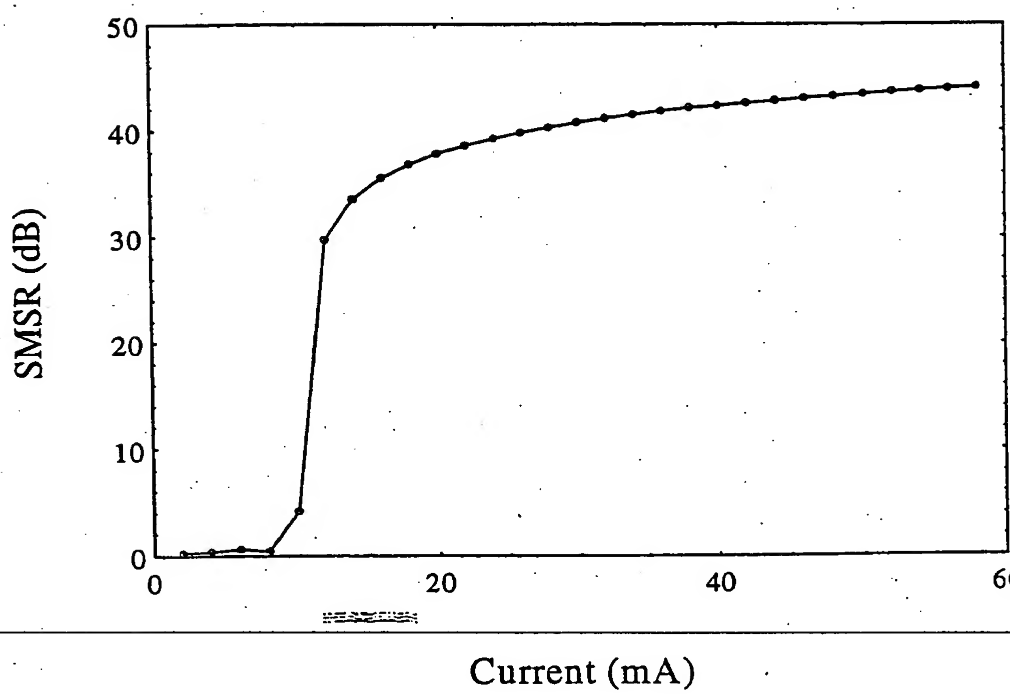


Figure 6.

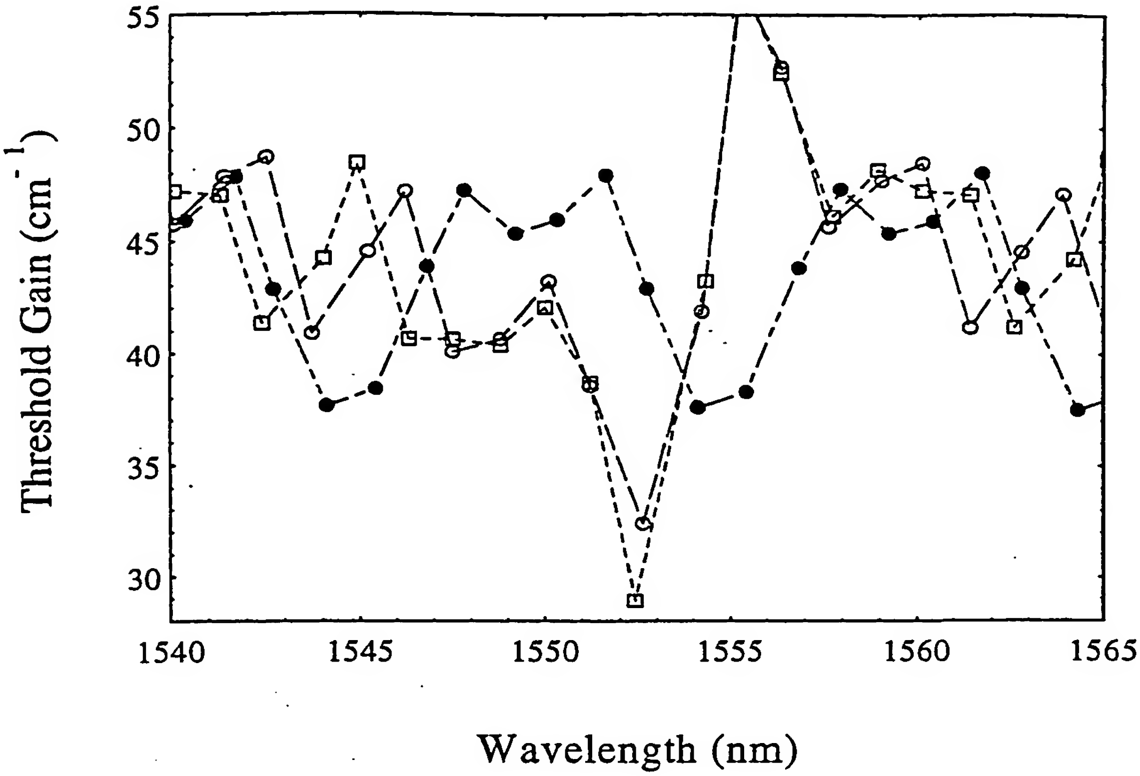


Figure 7.

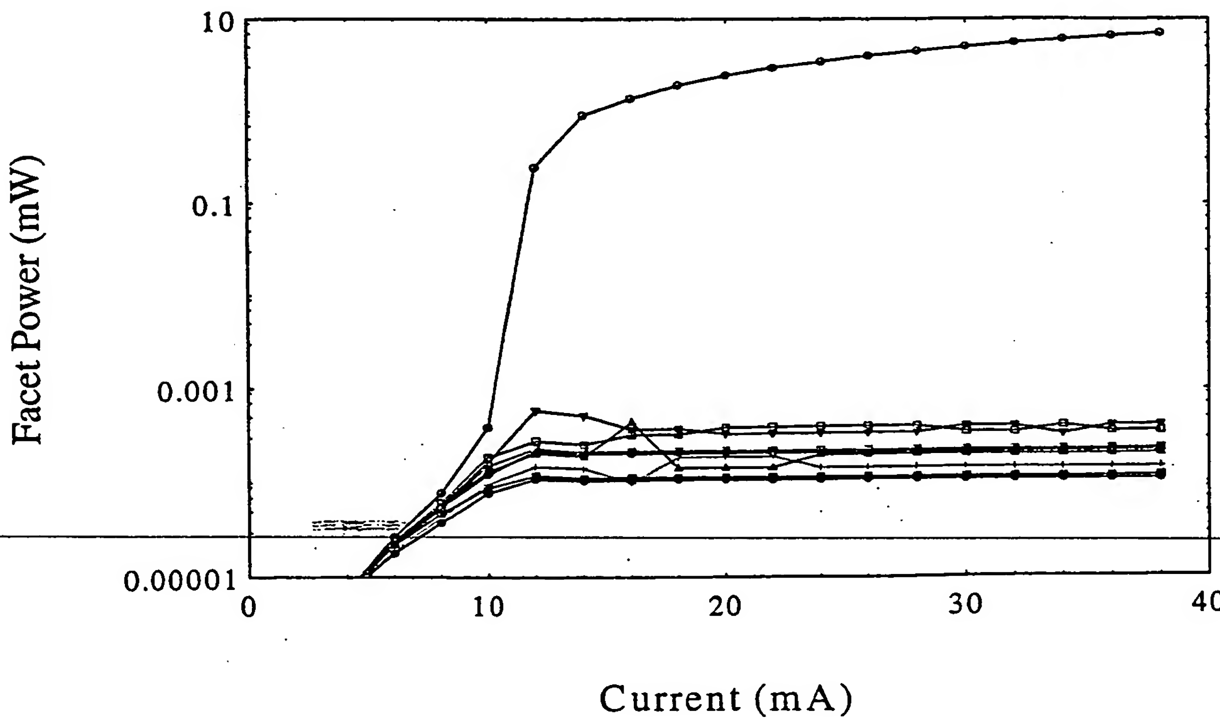


Figure 8.

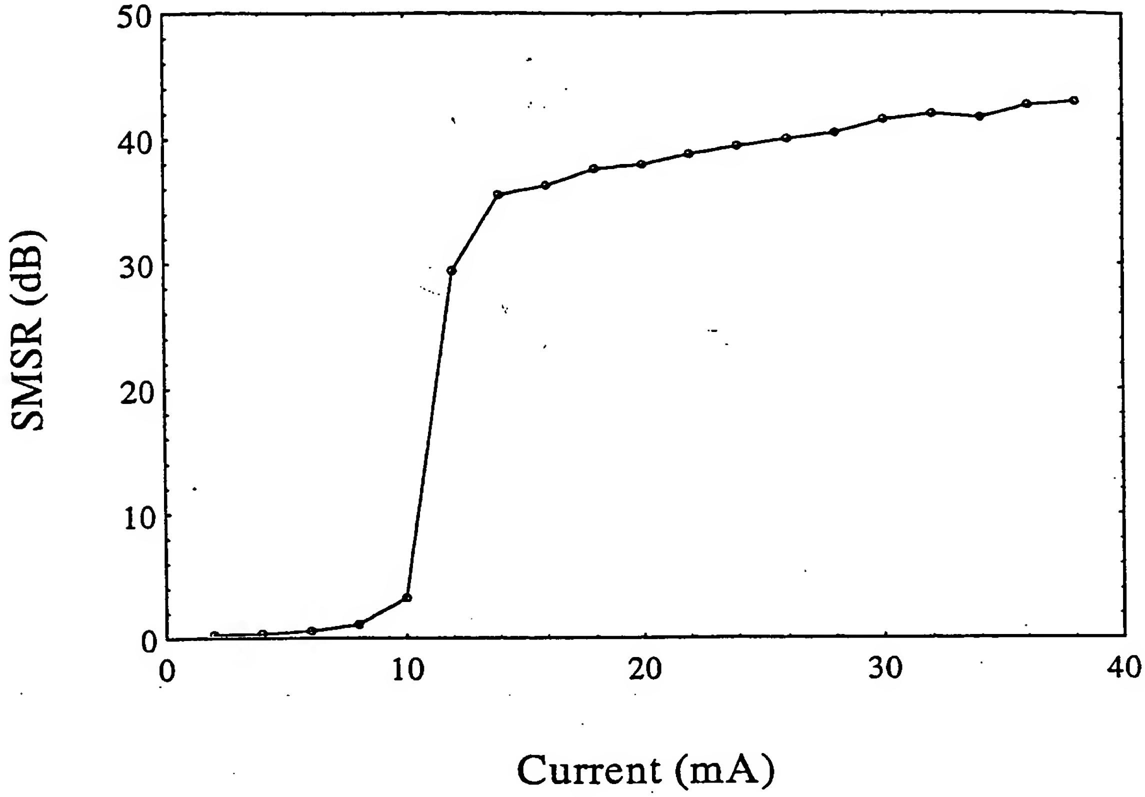


Figure 9.

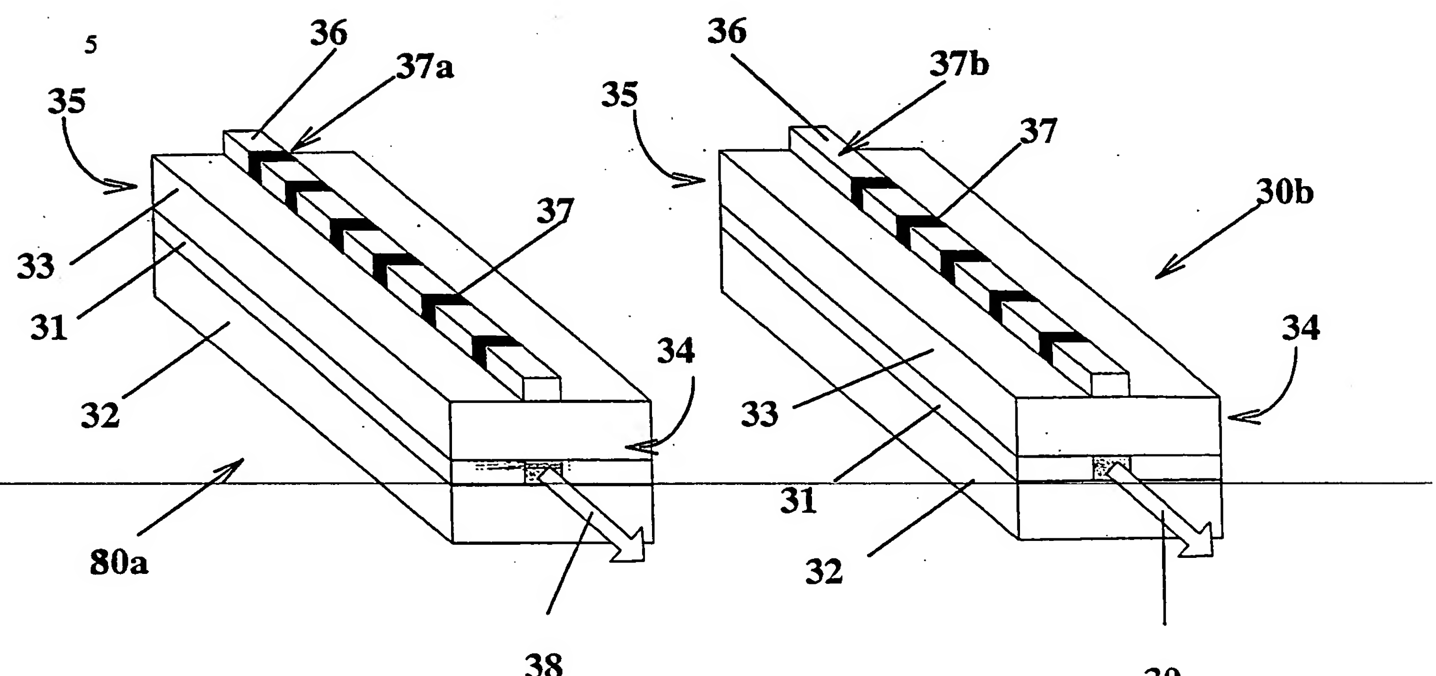


Figure 10.

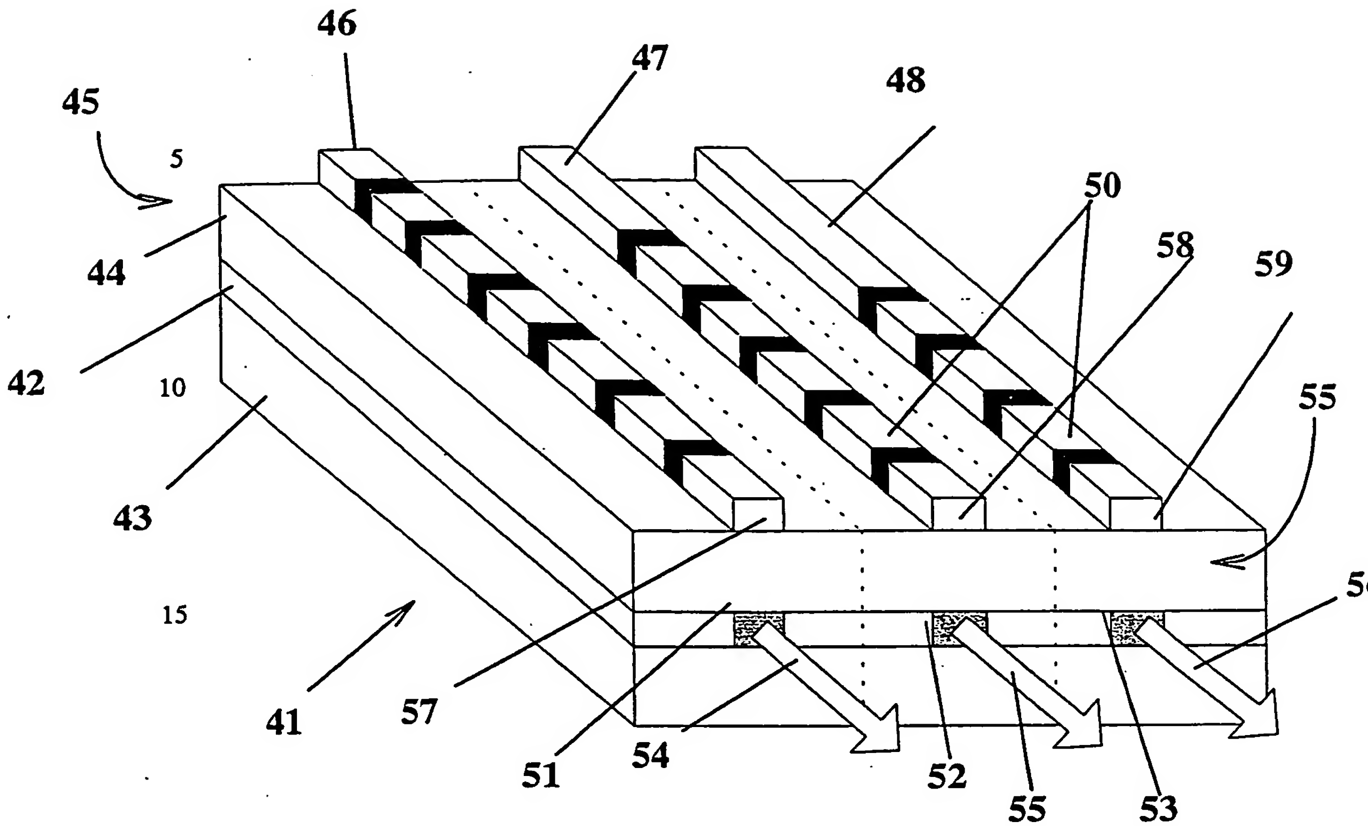


Figure 11.

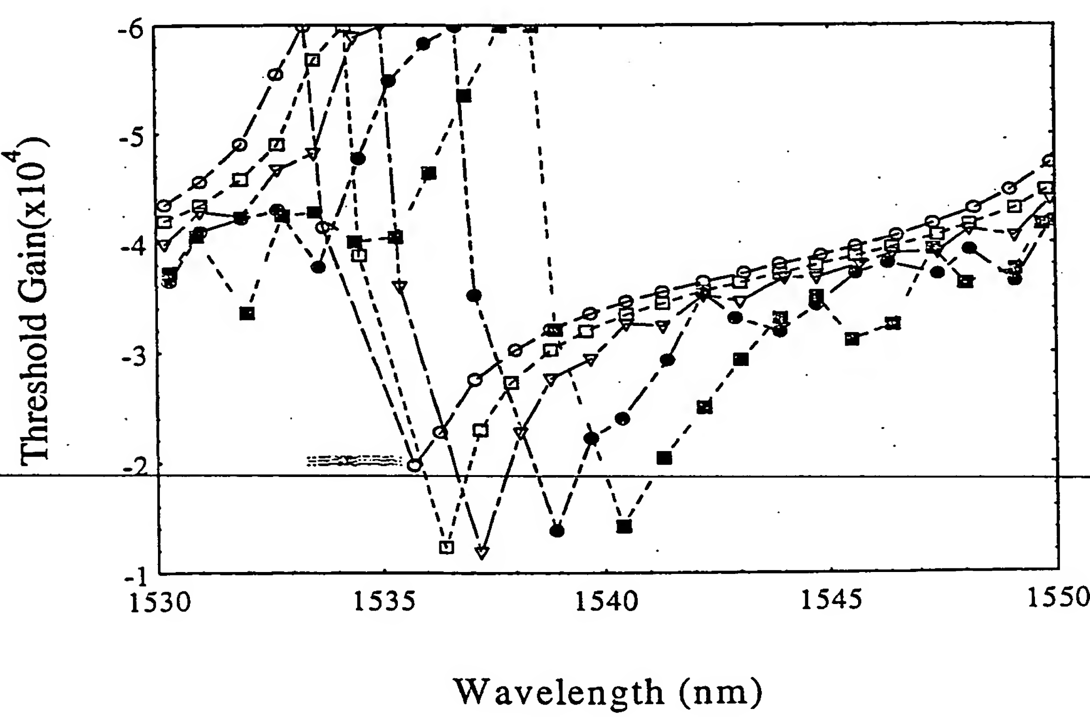


Figure 12.

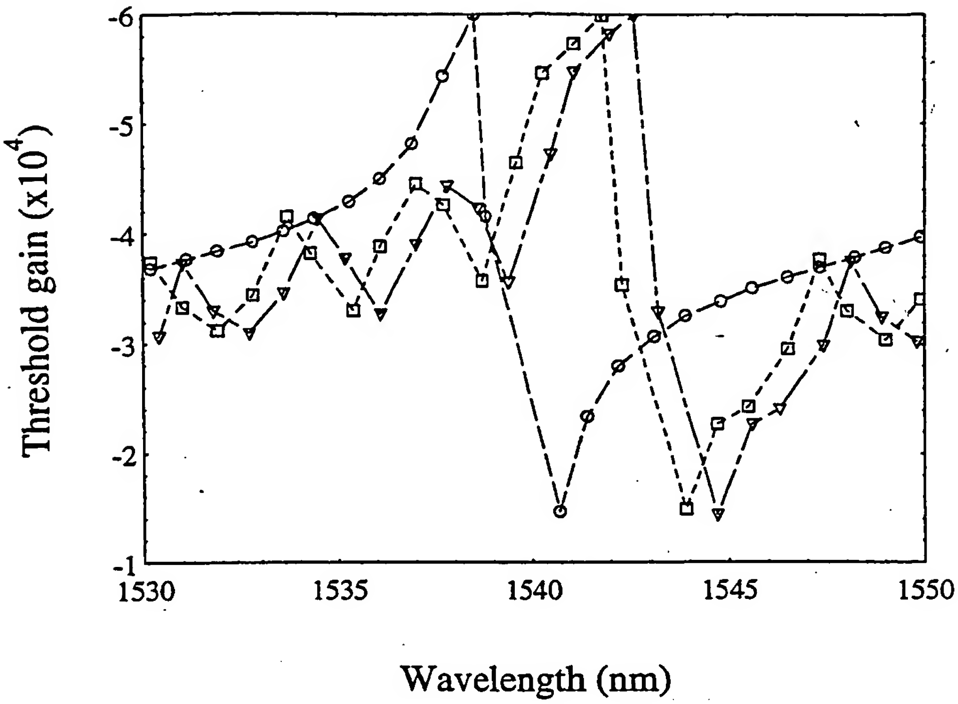
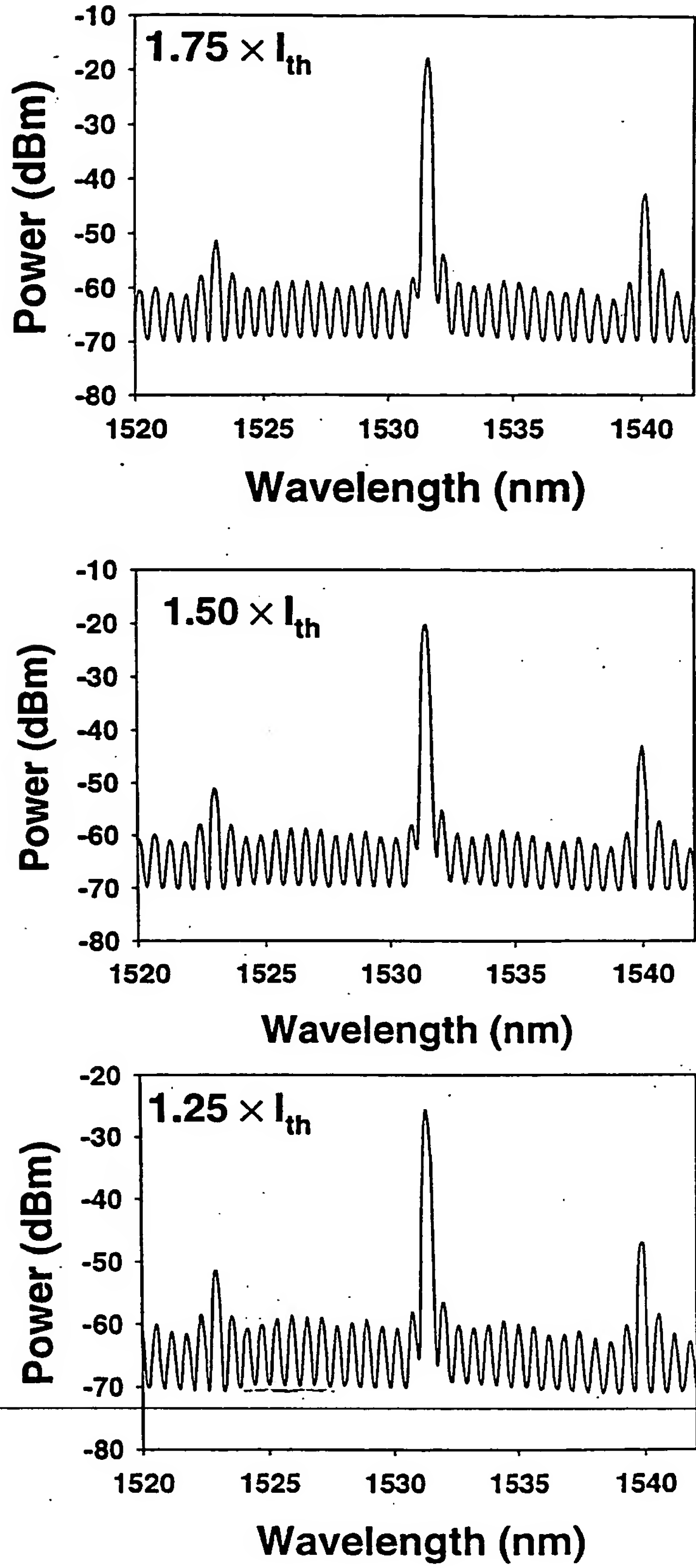

Threshold gain (x10^4)
-6
-5
-4
-3
-2
-1
1530
1535
1540
1545
1550
Wavelength (nm)

Figure 13.



1.75 × I_th
1.50 × I_th
1.25 × I_th
Power (dBm)
Wavelength (nm)
-10
-20
-30
-40
-50
-60
-70
-80
1520
1525
1530
1535
1540

Figure 14